Processes of Mud Volcanism and Shale Mobilization: A Structural, Thermal and Geochemical Approach in the Barbados-Trinidad Compressional System

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Abstract

This paper illustrates the diversity of subsurface sediment mobilization features in tectonically mobile regions in a shale-rich environment. In the studied area of the southeastern Caribbean, new geophysical acquisition in Trinidad and Barbados spectacularly show the widespread development of mud volcanoes and massive sedimentary extrusions in the interference area between the southern part of the Barbados prism and the active turbidite system of the Orinoco. Mud volcanoes are well developed along ramp anticlines, or on top of sigmoid rises, which are oblique with respect to the trends of the main folds of the accretionary wedge. The area also exhibits trends of structures corresponding to massive extrusions of well preserved turbidite and hemipelagic sediments that cut the surrounding sediments. Some of these extrusion structures are complicated by the development of collapse structures, calderas, and superimposed mud volcanoes. On some active mud volcanoes, heat flow measurements show high positive anomalies and bottom simulating reflectors that are

shallower compared to the surrounding areas and show high fluxes of fluid expulsion. The mobilized sediments expelled by the mud volcanoes are liquefied argillaceous and sandy material from deep horizons, and various shallower formations pierced by the mud conduits. Both in the Barbados prism and in Trinidad, the mud expelled is rich in thin, angular, and mechanically damaged quartz grains related to shearing and/or hydraulic fracturing processes. The exotic clasts and breccia result mostly from hydraulic fracturing. In Trinidad, the gas phase is mainly deep thermogenic methane associated with hydrocarbon generation at depth.

This paper emphasizes that subsurface, clay-rich formation mobilization notably differs from salt mobilization by the role taken by the fluid dynamics that control overpressured shale mobilization, and induce sediment liquefaction. Mud volcanism corresponds to fluid displacement, whereas massive sedimentary extrusion corresponds to large movements of stratified solid levels for which the deep cause could be the intrusion of mud plugs. Both are dynamic phenomena controlled by the development of overpressure at depth, contributing to sediment mobilization by reducing the strength within the overpressured layer. The regime of the expulsion of the fluids varies according to cyclic phases. Low-frequency cycles, notably the catastrophic events, are controlled by the dynamic development of overpressure. They could be related to the fact that when high excess pore pressure occurs at depth, hydraulic fracturing is responsible for opening the fracture network favoring successive fluid release and cyclic pressure decrease. Such processes could be enhanced by a threshold effect when fluids are over-saturated in gas. In that case, massive degassing of a large volume of dissolved gas at depth is possible, resulting in a sudden rise in fluid pressure and damage to the sealing properties of the sediments above gas-charged mud chambers.

Introduction

In tectonically mobile regions, and in shale-rich sedimentary environments, such as accretionary prisms and deep delta systems, subsurface sediment mobilization can be widespread and produce a wide diversity of structures. The aim of this paper is to illustrate this diversity of features using an example in the southeastern Caribbean, and to emphasize that shale tectonics differs from salt tectonics notably by the nature of the structures produced, and the fact that argillaceous mobilizations are time-dependant, dynamic phenomena closely related to the fluid dynamics. The area presented here is the interference zone between the Barbados tectonic wedge and the Orinoco turbidite system. In this region of the southeastern Caribbean, sedimentary mobilizations occur in a boundary region between the Caribbean plate and the South American plate, especially at the junction between the Barbados accretionary prism and the transform system of north-

ern Venezuela. Within this compressional and transpressional system, a spectacular, several hundred kilometers-long active belt of mud volcanoes and massive sedimentary extrusions develops from the Barbados tectonic wedge to the thrust belt of Northern Venezuela (Fig. 1). In this system, the mud volcanoes of Trinidad and Venezuela are only the emergent part of a widely developed phenomenon in the offshore area of the Barbados prism (especially its southern part). This is shown spectacularly by the results of the Caramba survey of the O/V Atalante in 2002 (Figs. 2, 3, and 4).

Structural setting

In the deep offshore, multibeam bathymetry, deep-towed acoustic sonar, and seismic data (2D and 3D) acquired in the southern part of the Barbados prism (Fig. 1) illustrate that mud volcanoes are spectacularly abundant and develop in different structural settings (Biju-Duval *et al.*, 1982; Valery *et al.,* 1985; Brown and Westbrook, 1987; Mascle *et al.,* 1990; Brown, 1990; Griboulard *et al.,* 1991; Gonthier *et al.,* 1994; Rutledge and Leonard 2001; and Deville *et al.*, 2003a, b, c, 2004; Fig. 1). The front of the tectonic wedge is characterized by an imbricate thrust system mostly devoid of active mud volcanism activity except in the southernmost part of the prism, where scarce mud volcanoes and associated calderas develop along the frontal fold. The main province of active argillaceous sediment mobilization is found within the core of the tectonic prism along ramp anticlines, on sigmoid rises of mud volcanoes and sedimentary extrusions that are oblique with respect to the main folds of the accretionary prism (Fig. 2), and along major transfer zones (especially at the eastern extremity of the El Pilar fault in the Barbados prism; Biju-Duval *et al.*, 1982; Griboulard *et al.*, 1991). On the slope between Trinidad and the Barbados prism, mud volcanoes are piercing through the turbidite draping (Fig. 3). The western part of the Barbados prism (Fig. 1) is characterized by the occurrence of extension structures superimposed on thrust tectonics (Deville, 2000), and the very inner part of the prism is devoid of active mud volcanism. Nevertheless, in the inner part of the Barbados prism, fossil shale intrusions and mud volcanism activity is known, notably on Barbados Island (Kugler *et al.,* 1984). Laterally, toward the southwest, the belt of mud volcanoes becomes narrower and emerges in Trinidad within the transpressive fold-and-thrust belt of the southern part of the island (Central and Southern Ranges).

Most of the offshore sedimentary effusive structures are volcano-shaped, their slopes increasing upward toward a top with a central crater. Some of them show concentric structures and up to kilometre-long mud flows. Calderas or craters are observed in different locations. In some cases, when calderas are superimposed over conic structures, this forms mud pies having steep flanks and a central relatively flat area probably

corresponding to ancient calderas that progressively is filled by mud flows. When the mud volcanism activity interacts with high sedimentation rate, as observed in eastern offshore Trinidad (Fig. 3, 4), subsurface mud volcano edifices show a "Christmas tree" geometry related to the stacking of successive edifices (Fig. 5). This is due to the fact that volcanic edifices developed during phases of low sedimentation (high stands), and they were progressively covered during phases of high sedimentation (low stands). The structure of the total edifice in that case is controlled by the cyclicity of turbidite sedimentation rate.

Mud volcanism processes

Cyclic activity: the pulse of the active overpressured sedimentary basins

As evidenced by the knowledge acquired onshore Trinidad, the mud volcanoes have different phases of activity, including catastrophic events followed by periods of relative quiescence characterized by moderate activity (Kugler, 1965; Higgins and Saunders, 1974; Yassir, 1987; Deville *et al.,* 2003a).

During catastrophic events, the material expelled consisted of high flows of gas, mud, polygenic clasts, and breccias from various formations of the sedimentary section (carbonates, sandstones, shales), as well as megacrystals of calcite and pyrite nodules. Such a catastrophic eruption occurred in Piparo on February 22, 1997, destroying several houses. This eruption was associated with the development of a network of open fractures, which acted as conduits for the mud expulsion. Some of these newly formed fractures exhibited east-northeast–west-southwest dextral strike-slip movements, associated with throws up to 15 cm, compatible with the present deformation regime along the central belt. Another such eruption occurred also in Devil's Woodyard on May 8, 1995. Short-lived islands associated with catastrophic eruptions appeared several times in the Columbus channel, offshore southern Trinidad.

The most famous site corresponds to the Chatham ephemeral island, the last eruption of which occurred on May 10, 2001. Since 1911, this is the fourth time that the mud volcano formed. Previous eruptions have occurred on August 1, 1964, December 21, 1928, and November 3 and 4, 1911; *i.e.,* a chronological spacing of 17, 36, and 37 years. More generally, from the available historic data it appears that each eruptive mud volcano has its own period of catastrophic activity; however, this period is highly variable from one volcano to another (Fig. 6).

During the phases of relative quiescence (but during which the flow expelled can vary significantly through time), the material expelled consists primarily of venting gas bubbles, mud made up of water, liquid

hydrocarbons, and solid particles. Onshore, gas bubbles diameters vary in size from millimeter to meter. The expulsion is active either in cones (griffons), or in mud pools and lakes. At some sites, the gas flows are relatively high; flows higher than 10 m^3 of gas per minute have been measured at Lagon Bouffe and Palo Seco. Generally, the mudflows are much more moderate compared to the gas flows (3 to 10 times lower). In some places, the mud volcanoes (notably in Marac and Erin) also expel significant flows of oil. In the offshore, the gas flows are also relatively high, but the gas phase is largely dissolved within the fluid expelled. This is due to the higher solubility of methane related to high-pressure conditions in deep water compared to atmospheric pressure. The existence of methane-charged fluid expulsion at the top of mud volcanoes is associated with the development of abundant chemosynthetic, biologic communities has been evidenced during scientific submarine dives (Jollivet *et al.,* 1990; Olu *et al*., 1997).

Heat flow measurements made offshore, on some active mud volcanoes in the southern area of the Barbados prism (Fig. 9) show positive anomalies (values higher than 100 mW/m^2 in the vicinity of several mud volcanoes compared with a background heat flow lower than 40 mW/m^2). In addition, near some active mud volcanoes, Bottom simulating reflectors (**BSRs**) are shallower compared to surrounding areas, suggesting that the stability field of gas hydrate in these areas is restricted to shallower levels. We interpret these anomalies as being related to heat diffusion associated with high fluxes of migration of relatively hot, deep-sourced fluids within the conduits of the mud volcanoes. It is worth noting that a high heat flow value at 230 mW/m^2 was measured in 1993 on a mud volcano (data from Foucher, published in Gonthier *et al*., 1994), whereas the heat flow measured at the same location, was only 38 mW/m^2 in 2002. This shows that thermal anomalies can vary drastically at short time frequencies, even at human scale.

We also studied the temperature distribution within the mud conduits of some mud volcanoes onshore Trinidad. The mud temperature is concurrently controlled by either the gas flux (because endothermic gas depressurizing induces a cooling effect), or by the mud flux (because mud is the convective vector for heat transfer from depth). We also noticed a very strong influence of the geometry of the conduits on the fluid circulation, and thus on the temperature distribution. Complex temperature distribution related to convection processes is seen in large conduits and pools. Indeed, especially in the bigger pools, the temperature distribution characterizes convective cells associated with an upward displacement of mud above the deep outlet and ring-shaped rolls associated with the burial of the mud on the flanks of the pools.

In simple, tube-like shaped, narrow conduits, the temperature is more regular, but we have observed different types of profiles, which have either downward increasing or decreasing temperatures. If the upward

flow of mud would be regular, we should expect increasing temperatures with depth, and progressively decreasing gradient within the conduits. However, the variable measured profiles, as well as time-variable measured temperatures at the base of the conduits, strongly suggest that the fluid flow expelled by the studied mud volcanoes is not constant but highly variable through short time-periods. An example of temperature variations in a very short time-period has been recorded at the Palo Seco mud volcano, where we observed cyclic variations with a frequency of about 10 minutes (Fig. 7).

Gas origin

Onshore Trinidad, the gas expelled by the mud volcanoes is primarily methane associated with moderate concentrations of ethane, propane, and carbon dioxide. This dry gas is characterized by a $\delta^{13}C$ of methane, which ranges between -52 and -33‰. Using a $\delta^{13}C(C_1)$ *vs* C_1/C_2 diagram (Prinzhofer and Pernaton, 1997), it is possible to show that a hypothesis of mixing between bacterial and thermogenic gas must be rejected; because, in this case, the bacterial end member would have methane $\delta^{13}C$ between -52 and -33 ‰, which are too heavy, and are incompatible with a bacterial origin (Fig. 8). Therefore, we consider that the analyzed gas samples have a strictly thermogenic origin.

The dryness of the gas is very probably due to a segregation process occurring during its migration from depth to the surface, adsorption on the solid grains of the mud, and solubility processes. The concentration in C2+ is higher in the sites where eruptions have recently occurred (Piparo and Devil's Woodyard, Columbus). Consequently, we suppose that adsorption occurs mainly during the quiescence phases, and that C2+ is released only during and after catastrophic eruptions. In the case of very recent (Neogene) gas generation, as observed in Trinidad, high flows of thermogenic gas could have been generated at temperatures around 150°C, similar to the equilibrium temperature of the deep reservoir that fed the mud volcanoes (Dia *et al.,* 1999).

The chemical and isotopic composition of the gas suggests a co-genetic origin with the hydrocarbon fields of Trinidad, both exhibiting notably atypical heavy values of $\delta^{13}C$ (CO_2), some values are approaching 30‰. This is a very unusual potential source of CO_2 in sedimentary basins. The source rocks of the hydrocarbon fields of southern Trinidad are the Cretaceous age Gautier and Naparima Hill formations (Rodrigues, 1988; Talukdar *et al.,* 1990; and Heppard *et al.,* 1998). Since the gas from the mud volcanoes is interpreted as being generated along with the gas of the hydrocarbon fields, we also attribute a Cretaceous origin for it. The analysis of noble gas radiogenic isotopes has shown that the gas expelled from the mud volcanoes exhibits

lower $^{40}Ar^*/^{20}Ne$, and $^{4}He/^{20}Ne$ ratios with respect to the gas within the deep hydrocarbon reservoirs, implying that the gas from the mud volcanoes has a shorter residence time than the gas associated with the oil fields (Battani *et al.*, 2001). As a result, the gas of the mud volcanoes cannot be issuing from a direct leakage from the hydrocarbon fields, but must come directly from deeper source areas.

Origin of the solid fraction

Fine particles

Combined X-ray diffraction and SEM studies in the Trinidad mud volcanoes, and on cores collected from mud volcanoes of the Barbados prism, have shown that the solid particles within the mud are composed largely of clays (kaolinite, illite, smectite, vermiculite), chlorite, and muscovite, as well as abundant grains of quartz, feldspar (albite, K-feldspar), carbonates (calcite, dolomite, siderite), titanium oxides (rutile, anatase), apatite, barite, and pyrite. Grain size varies from less than 0.1 µm, to more than 200 µm. The grains are supported within a very thin matrix consisting of a mixture of various clays, micas sheets, and small fragments (less than 5 µm) of quartz and albite with clearly angular shapes and internal microfractures, especially in the quartz. The mechanical damage probably results from shearing during compaction, or mud volcanism eruptive processes. Such quartz grains can represent more than 90% of the solid fraction within the mud.

In Trinidad, the study of nannofossils within the mud shows a systematic mixing of species ranging in age from Cretaceous to late Miocene. This suggests that the mud consists of a mixture of microscopic elements of various origins (from Tertiary formations and Cretaceous strata). This shows that, in Trinidad, the zone of initiation of the mud volcanism is necessarily at least as deep as the Paleogene, and probably the Cretaceous, because the mud intrusions do not crosscut thrust sheets involving Cretaceous-Paleogene formations.

In the offshore, the study of nannofossils in cores collected from the southern Barbados prism shows that the mobilized sediments in mud volcanoes are issued from various horizons including the Eocene, Oligocene (zones NP25 to NP21), Miocene, and Pliocene intervals in the inner part of the Barbados Ridge; whereas they are restricted to Miocene-Pliocene intervals (zones NN15 to NN21) at the front of the mud volcanism zone. This indicates that the initiation level of mud volcanism is not unique, but varies from older to-younger levels toward the front of the accretionary prism.

Clasts

Onshore, in the Trinidad mud volcanoes having recent eruptive activity (Piparo, Devil's Woodyard,

Columbus, Anglais Point, Moruga), exotic clasts (mainly centimetric to multi-decimetric) are found. The nature of the clasts is polygenic (carbonates, sandstones, shales, calcite, sulphur nodules, *etc.*). Some clasts are older pebbles initially interbedded within Tertiary formations and mobilized during eruptions, but most of the clasts (more than 90%) show angular shapes resulting from intense fracturing. This is not the case for the pebbles stratigraphically interbedded within the Tertiary sedimentary formations in Trinidad. Fractures are filled with carbonate cements (Ca and Ca-Mg). Frequently, real breccias made up of angular and initial joined elements are included within calcite crystallizations. We interpret most of the angular clasts and the breccia to be the result of hydraulic fracturing processes. Using nannofossils, it is possible to date the clasts expelled by the mud volcanoes. According to the ages obtained, these belong to Tertiary formations, ranging in age from Paleocene to Miocene (Deville *et al.,* 2003a). Cretaceous clasts are expelled by the Piparo mud volcano in the Central Range, the older elements being of early Barremian age. However, in this case, these clasts can come from the base of the Naparima thrust sheet; they do not necessarily have a deep origin.

Massive sedimentary extrusions

Nature and structure

Numerous geometrically complex, relatively large domes and complex rises, offshore Trinidad and Barbados, do not correspond to mud volcanoes, piercing shale diapirs, or simple folds. We interpret these structures to be the result of massive sedimentary extrusion. This is notably the case for several trends of prominent structures at the sea floor in the East Trinidad deep water whose shapes are roughly circular, or form complex rises with twisting axes. They constitute topographic anomalies of larger dimensions than the mud volcanoes. They generally have steep flanks and central areas showing a bumpy topography punctuated by pockmarks, and from place-to-place are covered by real mud volcanoes (Fig. 10). These structures are clearly different from the well-organized folds of the accretionary prism corresponding to ramp anticlines. They are also different from the mud volcanoes, which form well-identifiable, conical, eruptive edifices (Fig. 3).

Piston cores collected from the tops of these structures have shown that the sediments are not ancient flows of liquefied sediments, or piercing shale intrusions. Instead, these sediments exhibit a well preserved initial stratification. They are very different from sediments collected from the tops of mud volcanoes that generally correspond to the stacking of ancient mud

flows perturbed by fluid escapes and diagenetic processes generating carbonate precipitation (Fig. 11). On some structures, sediments are well bedded, sandy, turbidites (Fig. 11). On other structures they are characterized by hemipelagic sedimentation. We cannot exclude the possibility the hemipelagic sediments correspond to draping of inactive mud volcanoes or shale diapirs. However, the coarse-grained turbidite sediments (including coarse sand levels) found on top of some of these structures have been passively uplifted during the sedimentary extrusion. It is indeed very unlikely that such coarse-grained turbidite sediments could have been deposited on top of these isolated features.

On the acquired seismic lines, these structures at depth appear to truncate the surrounding intruded beds (Fig. 11). Consequently, these structures do not result simply from folding or thrusting.

Seismic data show that the cores of these extrusions have a relatively chaotic facies, and the identifiable reflectors show evidence of strong deformation. The only undeformed reflectors correspond to bottom simulating reflectors interpreted as corresponding to free gas trapped below the gas hydrate stability zone. The pinch-out geometry of surrounding strata indicates that the extrusion is progressive, and has developed over a long period of time (Fig. 11).

What are the deep causes for the massive sedimentary extrusion?

Obviously, massive sedimentary extrusions are the result of deep sedimentary mobilization processes. They probably correspond to passive uplift phenomena at the apex of deep intrusions. This is suggested by seismic imagery. However, for the time being we cannot define whether this results from intrusions of liquefied sediment, or simply from displacements of a solid body. Indeed, from the available subsurface data in the offshore (only seismic lines), it is difficult to determine if the deep process corresponds to mobile, overpressured plastic shale movements; *e.g.*, solid displacement as a shale diapirism process, or to intrusion of muddy material (liquefied sediment displacement).

'Fluid' hypothesis

It is possible that the deep intrusions initially correspond to mud migration that has formed intrusive chambers at depth. Subsurface information provided by petroleum exploration wells onshore Trinidad has shown that argillaceous intrusive plugs are frequently encountered at depth (Higgins and Saunders, 1974; Deville *et al.*, 2003a). However, even in the cored examples in Trinidad, it is difficult to determine the initial mechanical behavior of the intrusive material. We can suppose that the initially intrusive material is liquefied, and that progressively the mud has formed a kind of “mud cake” while the water phase is progressively

expelled at the surface, or into the surrounding strata. In several places in the offshore, the occurrence of fluid mud chambers at depth, underneath the massive sedimentary extrusions is suggested by the development of collapse structures and calderas superimposed on these extrusions (Fig. 11). Such collapses can be compared to similar, well known phenomena following eruptions during magmatic processes.

'Solid' hypothesis

An alternative interpretation is that these structures correspond to mobilization at depth of solid bodies that become mobile because of the development of overpressure, which can be related to low effective stress within shale (classic shale diapir interpretation).

Discussion and conclusion

The present-day understanding of clay-rich sediment mobilization remains relatively low and very commonly linked by comparison with the much larger literature on salt diapirism. However, processes of subsurface clay-rich sediment mobilization clearly differ from salt mobilization, notably by the crucial role taken by the fluid dynamics that induces sediment liquefaction and controls overpressured shale mobilization. In many cases, it is difficult to define precisely if sediment mobilization occurs as a liquid form (mud), or a solid form (mobile shale), even though this induces drastic changes in the rheology of the material involved and the modes of deformation (displacement of a very low viscosity fluid for mud, movement of solid bodies with a plastic behavior for the overpressured shale). This difficulty is enhanced by the fact that the rheology evolves through time, linked to the role of fluids. Stratified solid sediments can be liquefied, then migrate and intrude the sedimentary pile, and secondarily be associated with fluid loss so that they can solidify and form cohesive bodies. In addition, the transition between mobile overpressured shale and rigid shale overburden can be gradual and diffuse, as well as time-dependant. Progressive loss of fluids by mud volcanoes can reduce the overpressure and strengthen the shale layers.

Associated with the fluid expulsion, the mobile-sediment volume varies through time at depth. This can generate collapse and caldera structures in the overlying shallow levels. In the example studied, mud volcanism processes have a very large role in sedimentary recycling and in the deformation and the fluid dynamics of the area. In this study, it has not been possible to show real piercing shale diapiric activity. At the sea floor, the features that could be related to diapiric processes correspond to massive extrusions of sediments, during which shallow turbidites and hemipelagics have been passively uplifted. Fundamentally, mud volcanism corresponds to a displacement of fluids, whereas massive sedimentary extrusions correspond to significant solid movements, but for which the deep cause could be the

intrusion of mud plugs. Both are dynamic phenomena controlled by the development of overpressure at depth contributing to sediment mobilization by reducing the strength within the overpressured layer, which is necessary for mud extrusion by counterbalancing the mud load.

Overpressure generation is favored, in this tectonic and sedimentary context, by the conjunction of: (1) fast sedimentation rates of relatively impermeable sediments leading to compaction disequilibrium (sedimentary loading); and (2) compressive stress regimes inducing layer-parallel shortening and tectonic overloading. If fluids cannot escape fast enough relative to the pore space reduction, then the fluid generating the overpressure supports the load and lateral stresses. This is favored by the high deformation rates in accretionary prisms. This has an important role in the dynamic development of overpressure, which is typically a non-static phenomenon. In addition, gas hydrate occurrence in these deep offshore areas is likely to reduce permeability in the superficial levels, slowing fluid expulsion, and favoring overpressure. Moreover, the increase in temperature at depth induces the cracking of hydrocarbons, which is an additional factor for overpressure generation. Although the gas expelled by the mud volcanoes in deep water is most likely dissolved, the occurrence of free gas bubbles, especially in the shallowest areas, is also likely to reduce the density of the sediments, providing an additional factor favoring mobile sediment rise.

The fluid expulsion regime varies according to cyclic phases. This cyclicity within the mud volcano conduits occurs at different frequencies ranging from cycles of several years for the most catastrophic events, to cycles of several minutes gas and mud flows during the quiescent phases. The very high frequencies (short periods) could be simply related to the dynamics of two-phase flows (gas and mud) through the mud volcano conduits. However, low frequency cycles, notably the catastrophic events, are controlled by the dynamic development of overpressure at depth. These could be related to the fact that when high excess pore pressure occurs at depth, hydraulic fracturing is responsible for opening the fracture network favoring successive fluid release and cyclic pressure decrease. Such processes could be enhanced by a threshold effect when fluids are over-saturated with gas. In that case, massive degassing of large volumes of dissolved gas is possible at depth that could suddenly raise the fluid pressure and damage the sealing properties of the sediments above gas-charged mud chambers.

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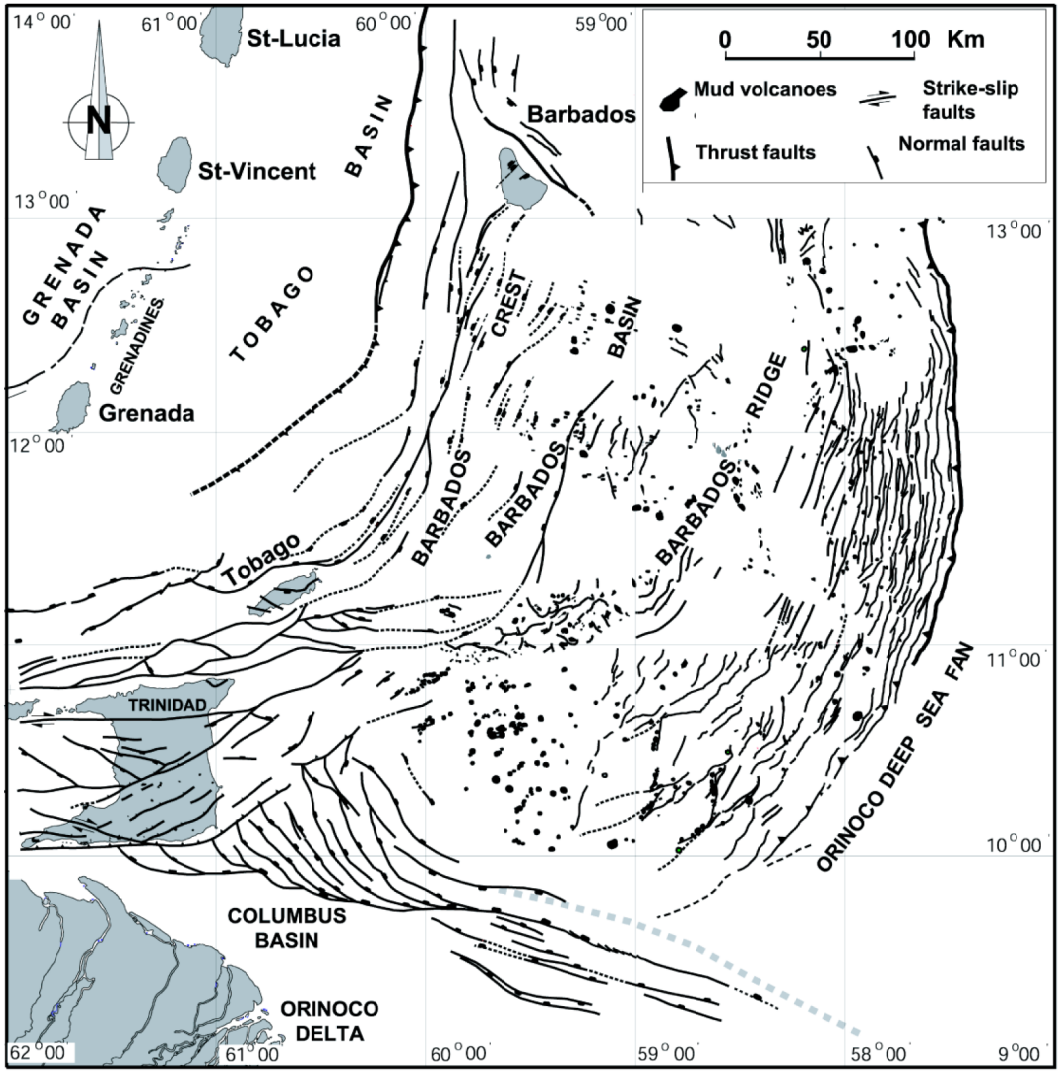

Figure 1. Location of the main mud volcanoes in the Barbados-Trinidad compressional system (simplified from Deville *et al.*, 2003a, b, c; 2004).

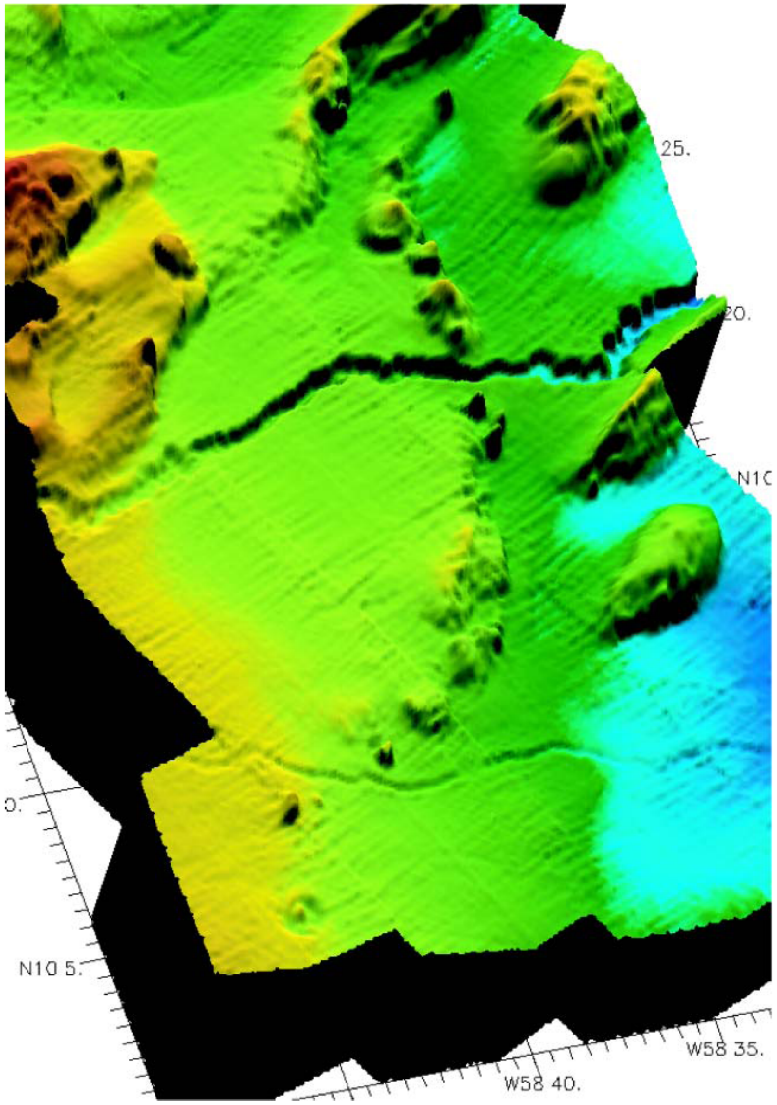

Figure 2. Sigmoid rise of mud volcanoes in the Barbados prism, oblique with respect to the structures of the prism.

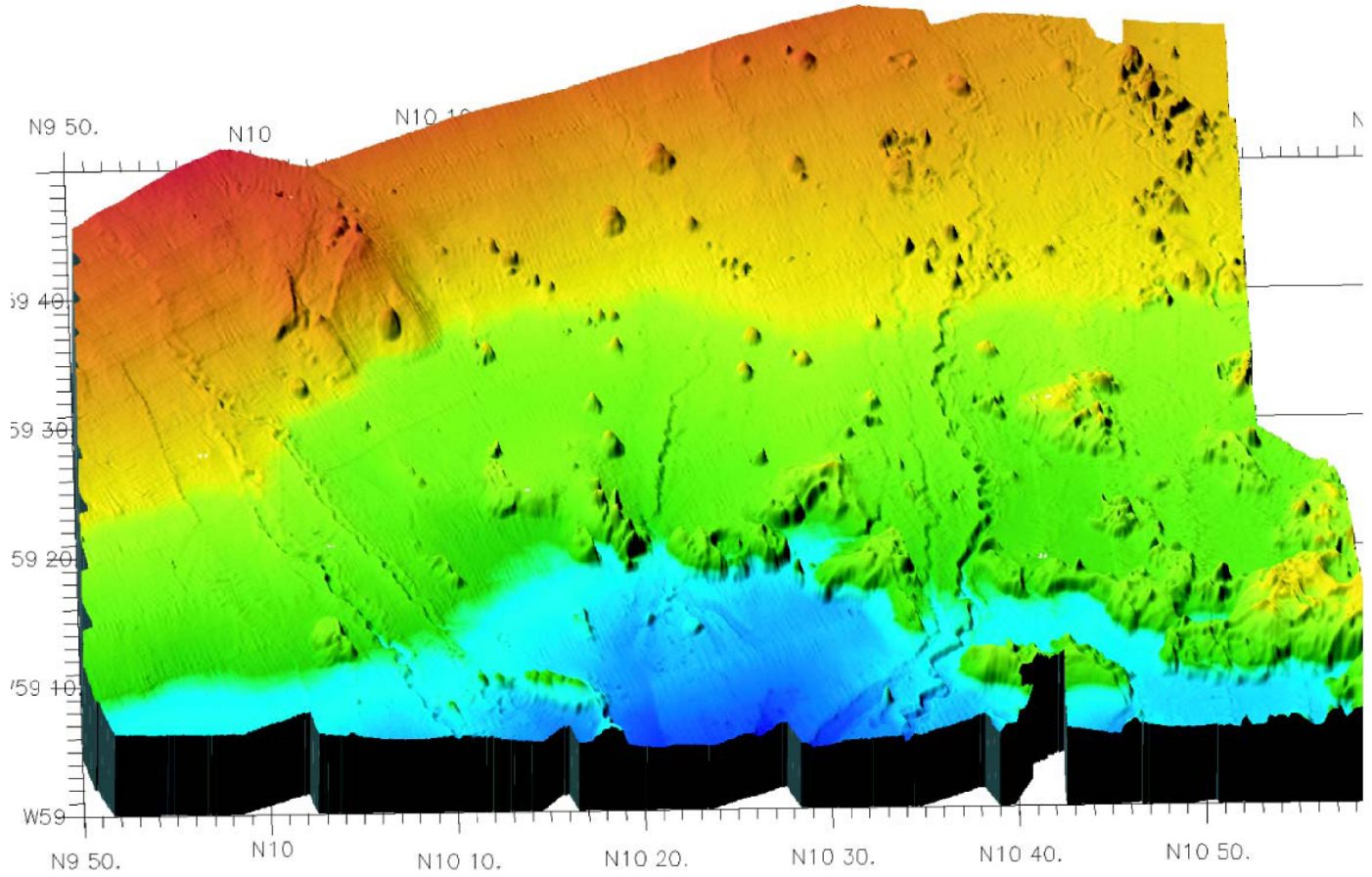

Figure 3. The slope between Trinidad and the Barbados prism (eastern offshore of Trinidad) pierced by numerous mud volcanoes and massive extrusion structures.

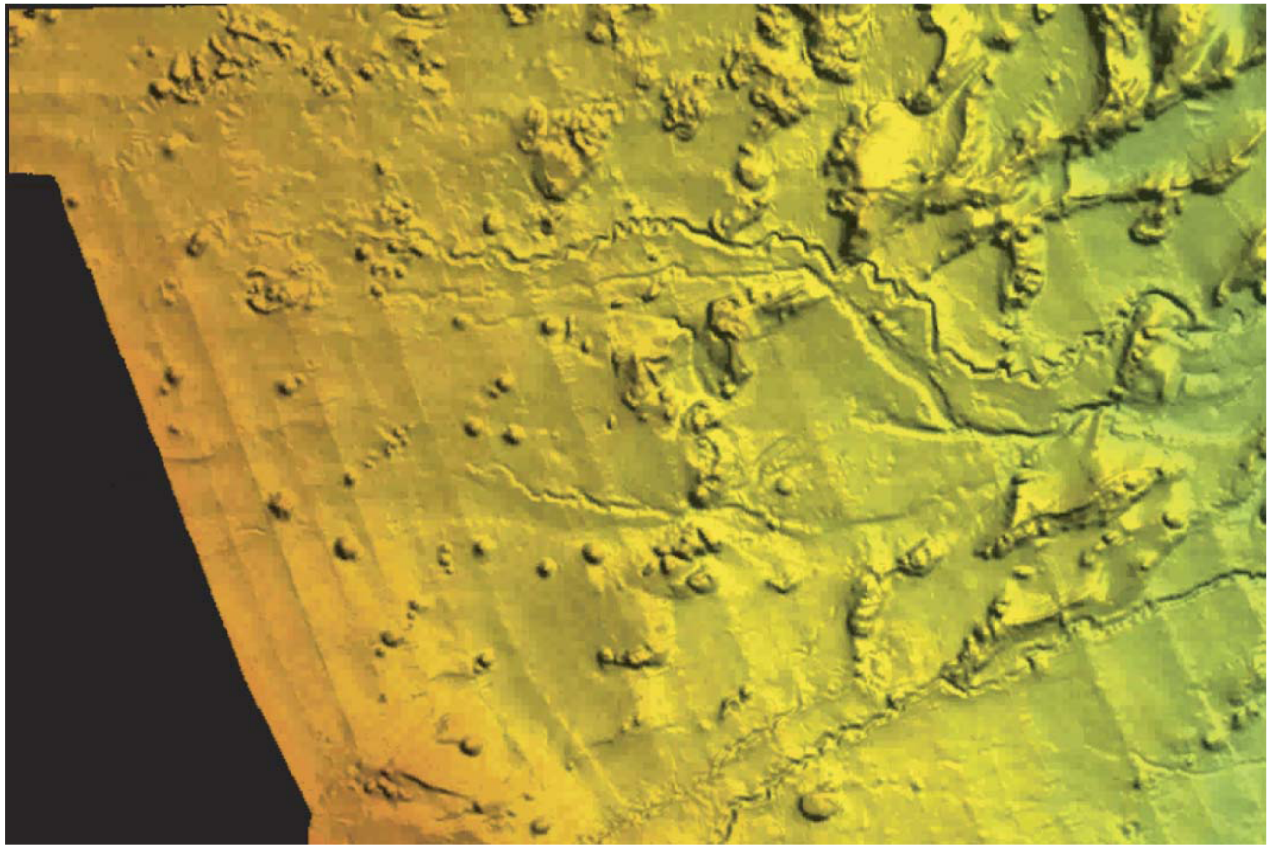

Figure 4. Video-animation. Flying over the mud volcanoes and sedimentary extrusion province of the junction between the southern Barbados prism and the Orinoco turbidite system.
Note: **QuickTime or the Windows Media Player must be installed on your machine to view this animation. Roll the mouse over the image until you see the tool. Click once and the movie will play.**

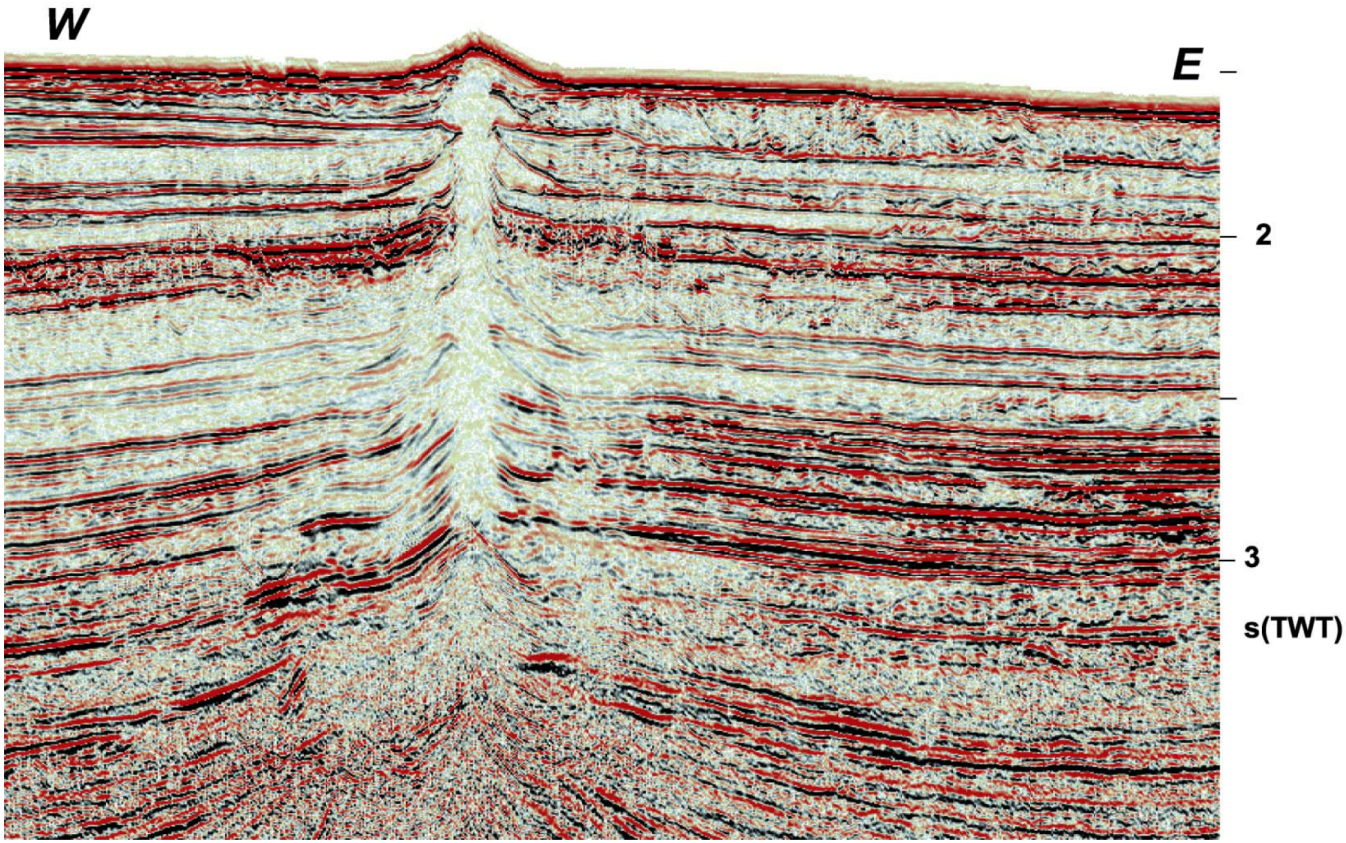

Figure 5. "Christmas tree" shaped mud volcano in the eastern offshore of Trinidad (courtesy Shell, Agip, Petrotrin). This seismic line shows the stacking of successive edifices of mud volcanoes. The structure of the overall edifice is controlled by the cyclicity of turbidite sedimentation rate. The edifices have developed during phases of low sedimentation (high stands), and they progressively have been covered during phases of high sedimentation (low stands).

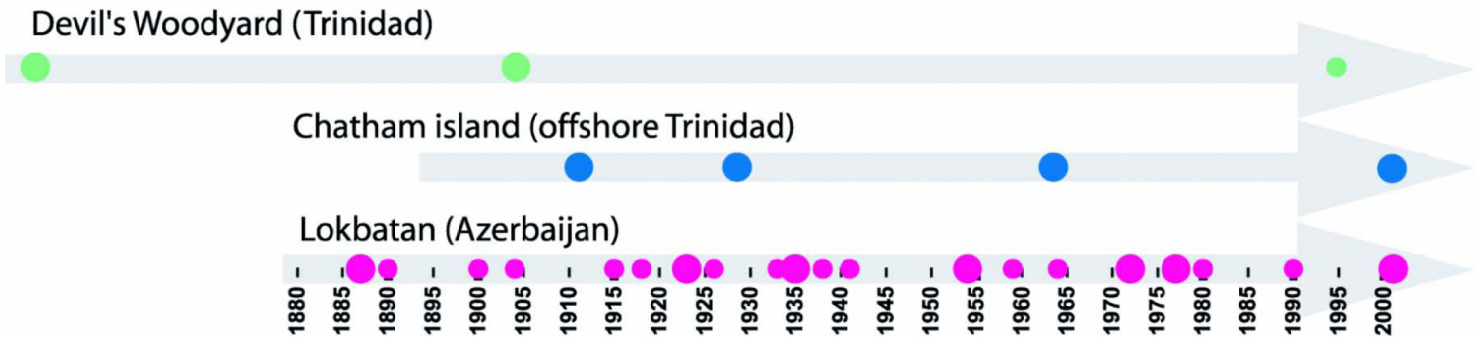

Figure 6. Catastrophic eruption frequency of some mud volcanoes in Trinidad compared with the frequency of the very active Lokbatan mud volcano in Azerbaijan. The frequencies vary from one mud volcano to another but each mud volcano has its own frequency of eruption.

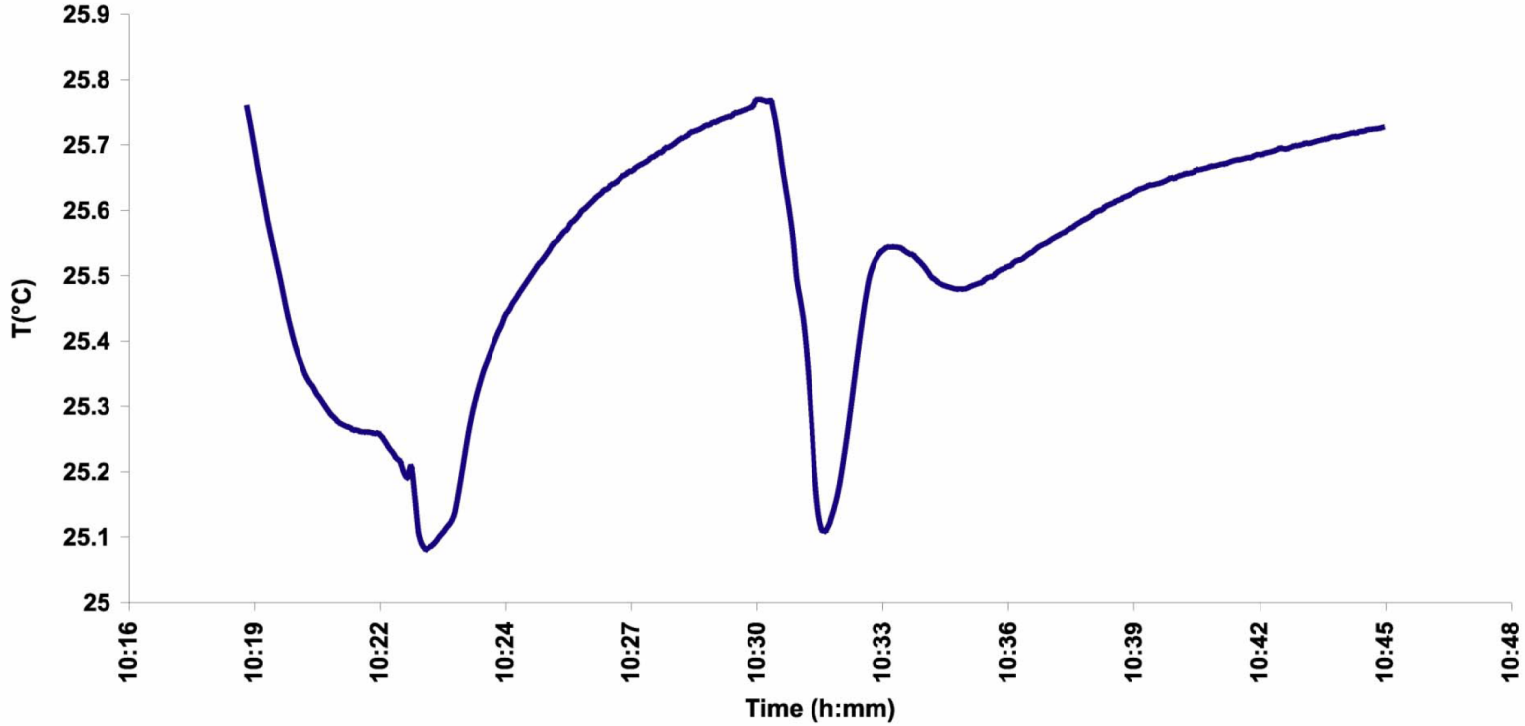

Figure 7. Cyclic temperature changes of the mud flow within a tube-line linear mud conduit at the Paleo Seco mud volcano in Trinidad (measures done at a depth of 34 m, 25 January 2002 between 10:19 and 10:45 am local time).

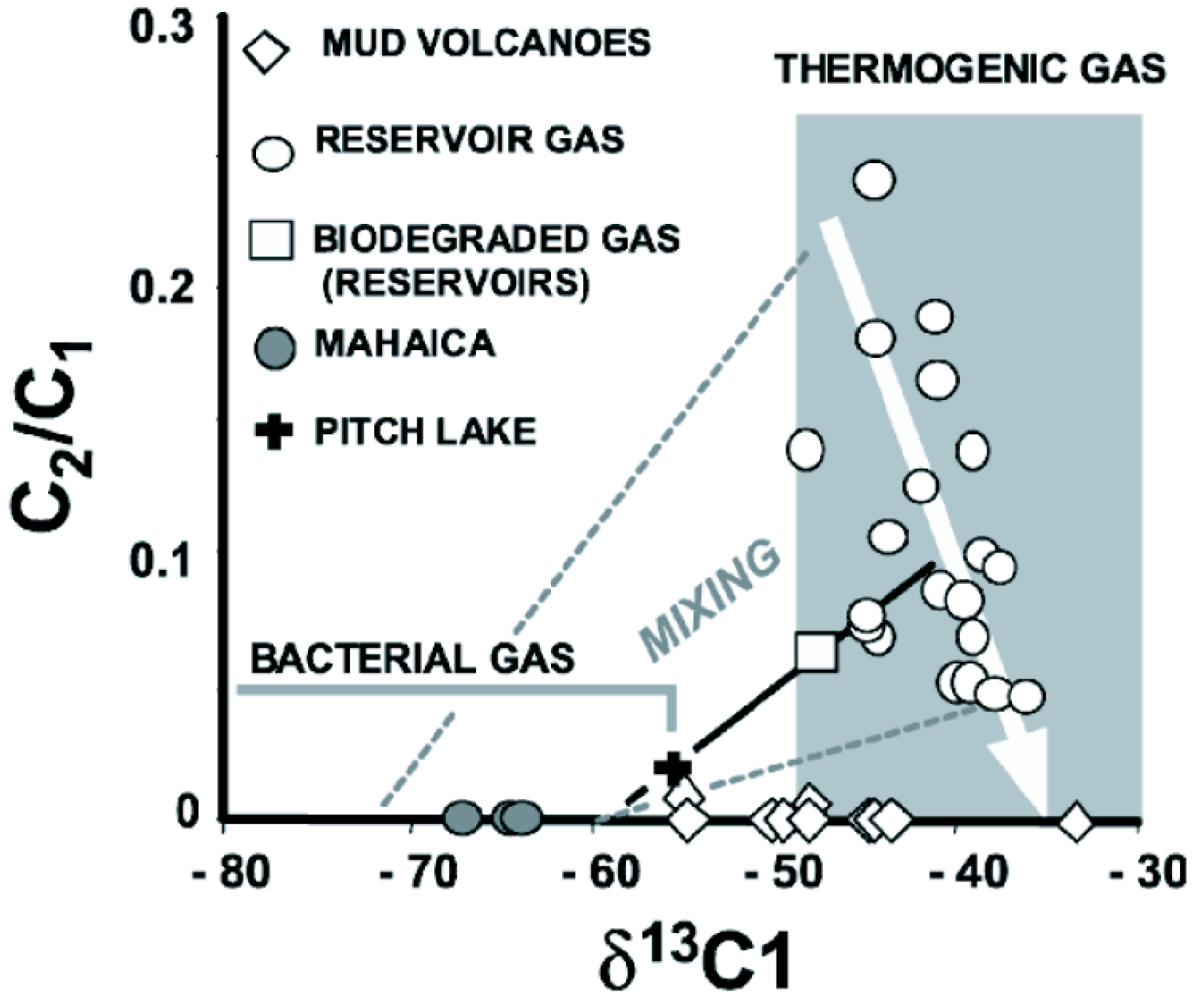

Figure 8. C_2/C_1 ***vs*** $\delta^{13}C_1$ **diagram in which a mixing between two end members is characterized by a straight line. Only three samples have bacterial contamination. Most of the hydrocarbon gas in the mud volcanoes has a purely thermogenic origin (from Deville *et al.*, 2003a, b, c).**

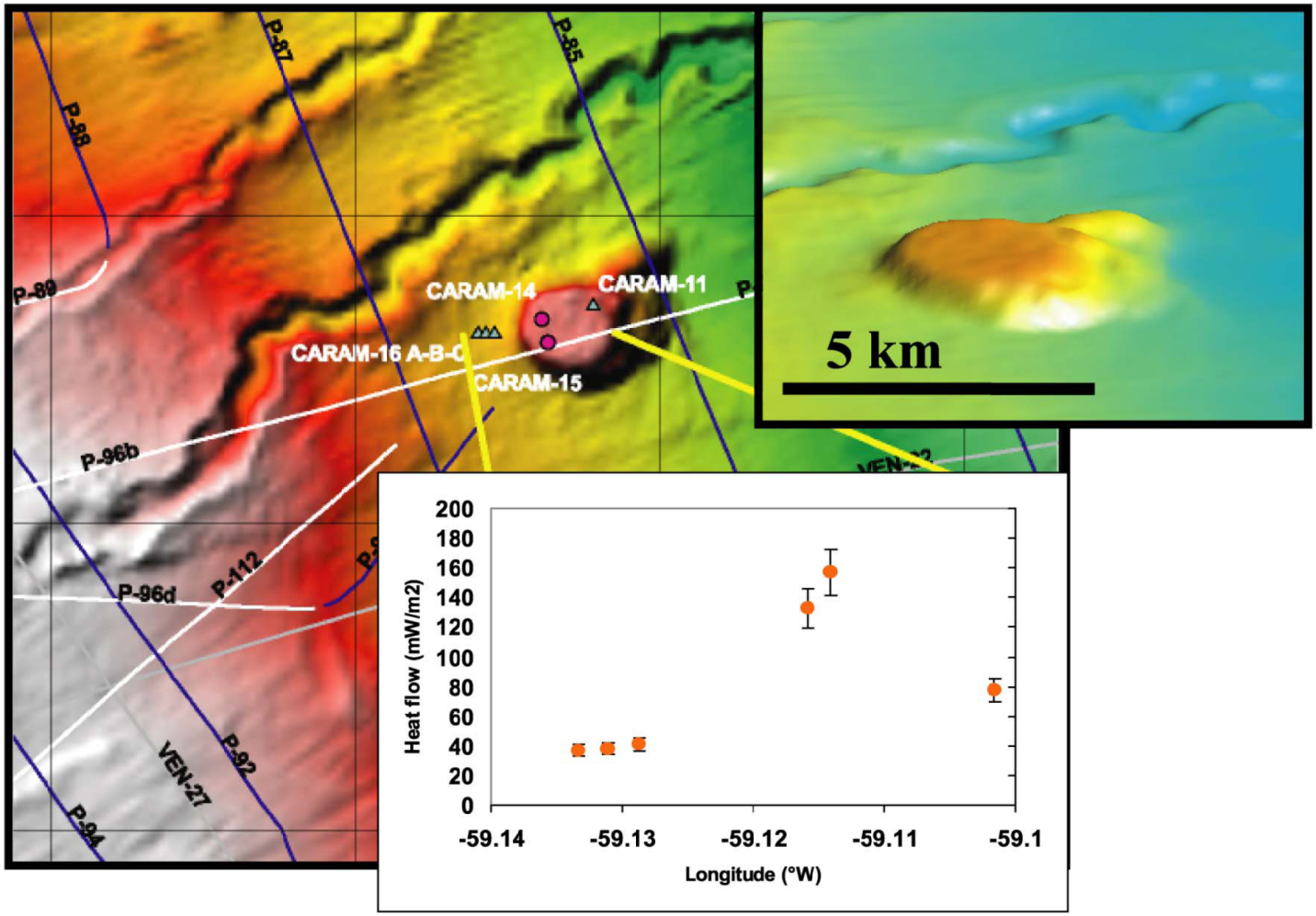

Figure 9. An example of a measured heat flow anomaly on the top of a mud volcano (mud pie) in the southernmost part of the Barbados prism. The high heat flow measured within this structure is about four times the value of the background heat flow in the surrounding sediments.

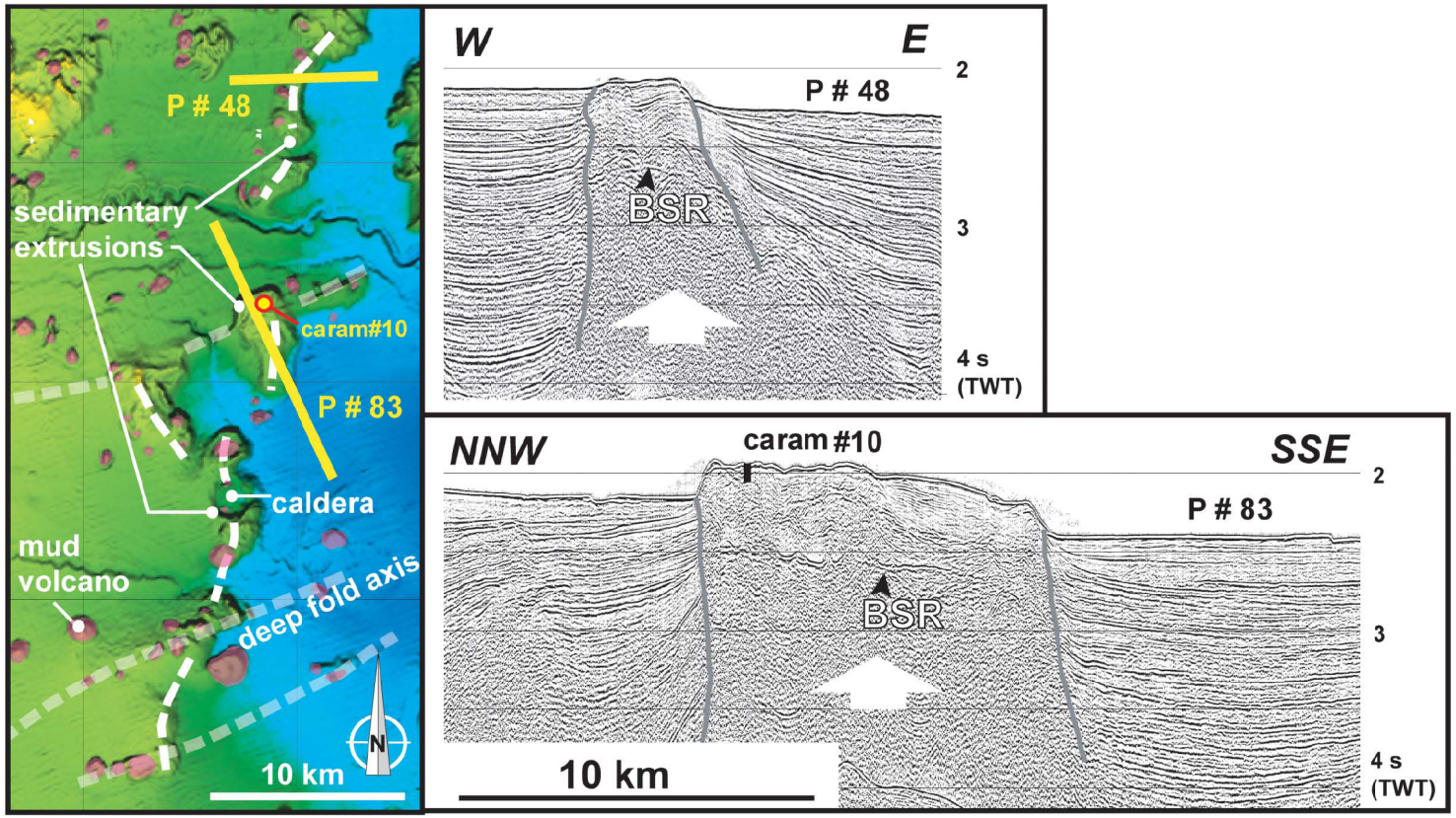

Figure 10. Massive sedimentary extrusions, in the east Trinidad deep-water area whose shapes are roughly circular or form complex rises with twisting axes (white doted lines). They constitute topographic anomalies of higher dimensions than the mud volcanoes, exhibit steep flanks and a central area with a bumpy topography covered in places by real mud volcanoes and complicated by caldera structures. Note that their axes are clearly oblique with respect to those of the deep folds buried under the turbidite sedimentation. The extrusion occurred progressively within the surrounding sediments. Note also that the core Caram #10, collected on top of one of these structures, contains well preserved coarse-grained sand turbidite sediments (Fig. 11).

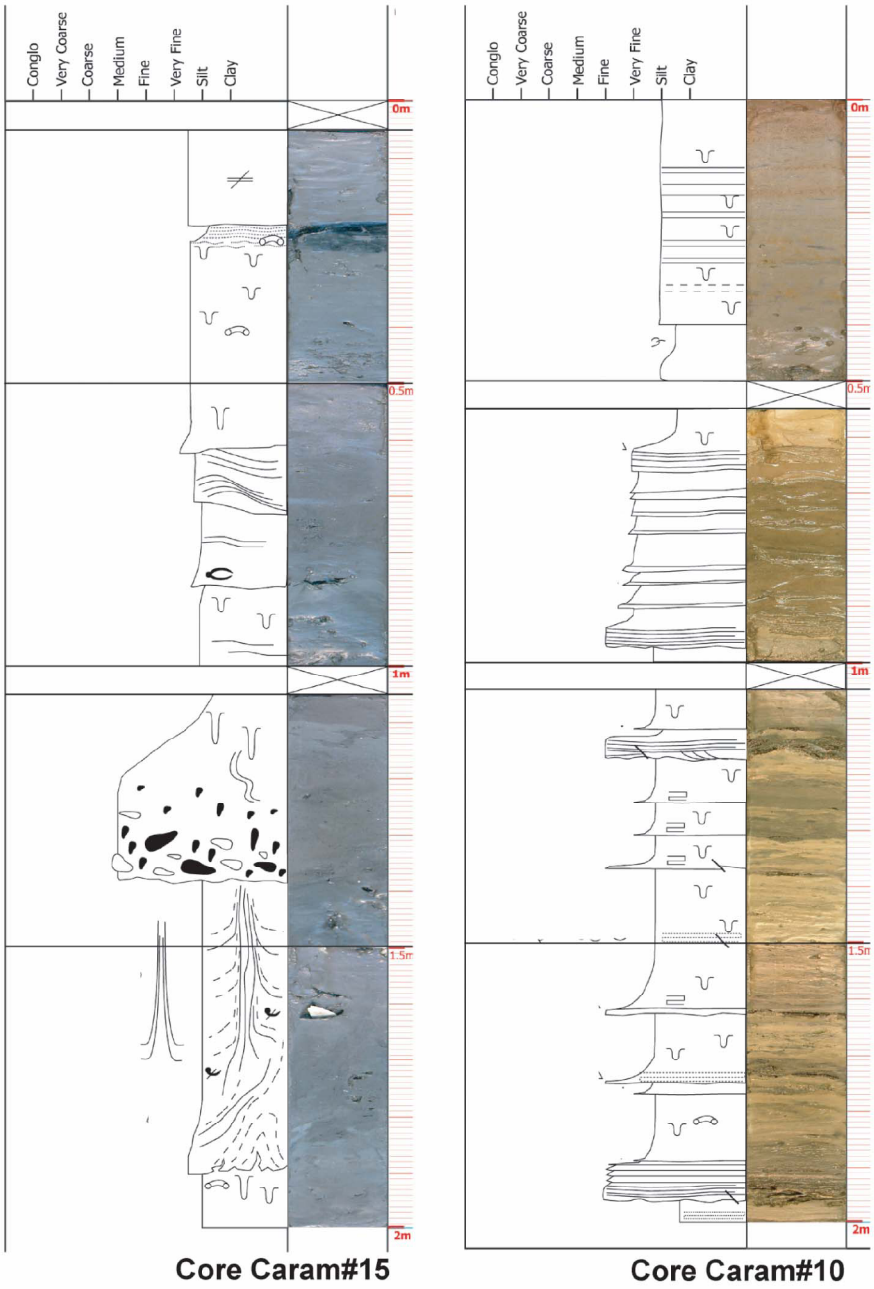

Figure 11. Two examples of cores collected in the offshore Trinidad. Core Caram #15 has been collected on the mud volcano shown in Figure 9. It is made up of the stacking of successive mud flows with reworked mud clasts, diagenetic carbonates elements at the base and deep benthic shells. These flows are perturbed by fluid escape and hydraulic fracturing. Core Caram #10 was collected on the massive extrusion structure presented in Figure 10. It is made up of well-preserved sandy turbiditic sequences, with coarse- to medium-grained sands.